

COMPARISON OF INTERCONTINENTAL WIRELESS AND WIRED POWER TRANSMISSION

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Abstract: An economic comparison is made using past studies and contemporary estimates of wireless vs. wired power systems in the range of 1MW to 10 GW, for transmitting electric power between continents. Installed system costs in terms of \$/km-MW are plotted as a function of the power level.

Wired power systems considered are open wire lines (OWL) AC, DC and an RF form, undersea or buried cables, and buried TE₀₁ mode microwave circular waveguides. Wireless power transmission (WPT) systems of retrodirective phased array transmitters and rectennas are costed for point-to-point paths on the Earth's surface for short ranges and via orbiting reflectors. Power Relay Satellites (PRS) for long range systems. Transmission system losses are compared and discussed.

The well developed OWLs are the lowest cost electric power transmission system. However for intercontinental, transmission across a body of water undersea cables are typically utilized, and the cost is at least an order of magnitude over land based OWLs.

High power WPT systems costs appear comparable to the undersea cables costs for the short range (e.g. Strait of Gibraltar, 15 km) but are potentially lower cost for longer range (e.g. Brazil to Martha's Vineyard floating Rectenna, ~6500 km) PRS systems.

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I. INTRODUCTION

Electric power transmission can be divided into wireless and wired forms. Wired power transmission is familiar as the open wire lines (OWL) strung from insulators on wooden or metallic or concrete poles. Not so familiar are waveguides such as enclosed metallic structures or wave-guiding dielectric coated single conductor Goubau or G-lines.

Wireless power transmission (WPT) may be reflected sunlight, laser, IR, and radio or microwave beams. The latter had been most developed by Bill Brown [1,2,3] with a key demonstration at 2.388 GHz of over 34 kW delivered over 1.6 km at Goldstone, CA in 1975 [4]. No physical conductors are disposed between the transmitter and the receiver of a wireless power transmission system.

The curvature of the Earth's surface enters into consideration not only for the long range power relay satellite (PRS) links, but also for transmission paths above about 25 km in length. The TE₀₁ waveguide must be nearly perfectly straight for maximum efficiency of introducing no higher order modes. The line-of-sight, above ground microwave links beams must adequately clear the bulge of the Earth with an additional personnel safety clearance.

Transmission losses for the various systems should be compared as they are significant and are very different as they have various contributors, depending on the type of system. The losses factor into the system's overall economics. In the wired systems, the current flow in conductors leads to heating losses. There are additional nonconductor losses where dielectrics are in the electric fields. Induced magnetic field losses arise in some nearby structures and depending on the frequency and line length, there are radiation losses. Corona losses occur due to the high voltages and conductor radii and condition of the ambient atmosphere and weather phenomena. Buried or submarine cables systems and typical OWLs have around 95% power output to power input transmission efficiency, depending on conductor current loading. For example, Los Angeles Department of Water and Power "postage stamp" loss rates on the Pacific DC or Intermountain DC segments are 6.36%. Proposed intercontinental sea cables may be designed for transmission losses around 2% per 1,000 km.

In the wireless systems the main irreducible losses are beam coupling due to radiation diffraction or spillover losses, wherein the power flux density beyond a certain level is uneconomical to intercept and rectify and it is not cost effective to build larger diameter transmitters or taper the aperture more to focus the beam tighter or increase the beam efficiency. Propagation losses due to molecular resonance absorption and particle scattering from elements in the beam are of consequence, depending on the RF wavelength and the ambient atmosphere constituents and weather conditions. The WPT equipment has I-squared-R losses due to current flow in its terminal equipment, along with dielectric losses, in addition to the basic DC-RF converter losses. The current efficiency record for measured output DC to input DC power in a WPT system is only 54%. (The least efficient element in the transmission chain was a conventional microwave oven

magnetron at only 72% DC to RF conversion efficiency.) The reference SPS WPT system design efficiency from the rotary joint DC input in GEO to the rectenna DC output on the ground was 59.3%.

Other projected WPT system overall transmission efficiencies may in the future be over 60%, but this still handicaps such systems economically as compared to wired power systems, except in cases where it is impossible to erect poles or towers or to lay cables; generally involving space or airborne platforms.

Compare the existing measured microwave power transmission magnitude record (34kW) to the state of the art multi- GW +/- 750 kV DC lines. There is no real comparison as yet in terms of the power level that has been handled. Thus, really meaningful economic comparisons must await higher power level WPT applications such as Space Solar Power (SSP) [5] and Interterrestrial power beamers [6]. Until then, we can only make crude cost estimates to compare with the existing well developed wired power systems. This paper will examine the question of are there any instances where WPT may compete with wired power distribution systems for delivering power over intercontinental distances.

Intercontinental distances will range from the 15 km across the Strait of Gibraltar to over 6,500 km from Itaipu, Brazil to near Martha's Vineyard, MA in the US.

The comparison figure of merit will be in terms of the lowest cost, per unit distance - unit of power product. We have chosen dollars per kilometer - megawatt, \$/km-MW. A scatter plot as a function of power transported will be used to collect the data and then trend lines will be drawn if applicable.

We will present the approaches, the technologies, discuss the safety

considerations, issues of right-of-way and then present the cost data and estimates, before drawing conclusions and making recommendations.

II. TYPES OF WIRED POWER TRANSMISSION

Three types of wired power transmission will be examined. First is open wire lines (OWL) [7], which can be either ac or DC. Second is high voltage cables [8], under ground or under water, and again ac or DC. (We will leave the nascent superconducting lines till a later era.) Plowing and trenching are both used to emplace subsurface cables. Dave Criswell suggested that directional drilling might be used to emplace some cables in difficult environments for short ranges.

The third type of wired power transmission is circular microwave waveguide [9], ac only at RF frequencies and principally in the TE₀₁ mode. (A fourth type known as the Goubau Line or G-Line dielectric coated conductor surface wave-guiding structure exists, but no commercial applications for long distances have been costed, to the author's knowledge.)

The TE₀₁ mode circular waveguide cannot follow the curvature of the Earth if it is to be single mode with the lowest loss. Slow bending is possible with dielectric liners and corner turning is possible with mode converters, but at the expense of higher insertion loss and complexity, i.e. added cost.

III. TYPES OF WIRELESS POWER TRANSMISSION

We examine two types of wireless power transmission. First is direct [10] from transmitting array to rectenna [11]. Short (< 10 km) ranges on the Earth can resort to tall structures or available terrain elevation to place the line-of-sight wireless beam safely above people and equipment. At longer ranges, (> 25 km)

the Earth's curvature requires that the transmitter and receiver be placed on high elevations or tall structures in order for the beam to have path clearance, whereas OWL and cables can readily follow the Earth's curvature. Thus, direct WPT on the Earth's surface is probably limited to < 40 km distances, due to structure-environment and beam safety consequences.

The second type of WPT is via relay reflector [12, 13, 14, 15] between the transmitter and the rectenna. The latter is particularly in response to the fact that two well separated points on the surface of the Earth cannot see each other, due to the curvature. A plane or elliptical reflector can be used, but needs to be at an altitude that is mutually visible to transmitter and rectenna. For long intercontinental hauls, GEO orbiting reflectors are probably required, otherwise a fleet of many reflectors and moving beam transmitters and wide angle rectennas are necessary, at added cost [16].

The diameter, surface precision and orientation of the reflectors are key to the PRS systems. The Bekey 35 GHz system proposed 2 Km diameter transmit and receive arrays with an orbiting reflector of 200 m diameter active controlled film membrane. A.D.Little proposed a 4.7 km diameter transmitter and receiver with a 2.4 km diameter reflector at 2.45 GHz for the Brazil to New England 6,500 km link. Boeing proposed a 2.2 km diameter reflector at 5.8 GHz with flatness of an eighth of a wavelength, (~ 0.6 cm) with active control and attitude control of 1/4 arc second requiring about an 80 tonnes of propellant resupply every four years.

Shorter range (<500 km) power relay systems may in the future use high altitude stationary platforms with an internal moveable mirror [17] contained in the airship dielectric envelopes for example. An increasing portion of the power beam would have to be taken at the airship in high winds and used for

propulsion power to maintain station keeping and mirror positioning. The required power would scale as the cube of the wind velocity.

Pairs or more of the geostationary high altitude platforms could extend the power delivery range as in an elevated beam waveguide system with multiple mirrors, but with more diffraction losses and added system complexity. Beam waveguides in the sky could however, provide flexibility for relatively rapid rerouting of power to aid utility load servicing in emergency or other situations, given that certain ground based equipments were in place.

The economics of such high altitude platform power transmission systems have not been modeled to the authors knowledge, although low power communication links have been briefly investigated.

IV. COMPARING SAFETY AND OTHER PERFORMANCE CHARACTERISTICS

Both wired and wireless power transmission have innate characteristics that can be hazardous and disruptive. The economics are such that it is desirable to contain the electromagnetic fields in a small cylindrical beam and when combined with the high power levels, the space occupied by either system can be hazardous to life and property [18]. Therefore, right-of-way is a desirable concept for electromagnetic power transmission.

Over the years, people by education and some animals have become conditioned to avoid the intense fields associated with power transmission by wires. Not so for wireless power transmission, and thus education and other means such as physical separation, signage, imminent intrusion detections and generator interlocks, etc., must be provided. These safety cost should be reflected in both

wired and wireless power transmission comparisons.

Except for the closed metallic waveguide and the shielded cable, all other forms of wireless or wired power transmission produce potential radio frequency interference. Think of the hum in your car radio as you pass underneath a high voltage line, especially in precipitation. Similarly, for microwave beamed power, it is scattered by diffraction and reflection from precipitation. Mitigating these costs such as with larger diameter conductors and microwave band pass filters are costs that should also be included for fair comparison.

Simply inflating historical estimates will not make a fair cost comparison for all of the data in the single plot. For example, the underground waveguide cost will certainly be more today due to inflation, but may be lessened by the technological advances in excavating tools for example.

Regarding RF power levels of existing systems, the largest near CW power level phased array transmitters (PAVE PAWS) are only about three-quarters of a megawatt power level at UHF (420-450 MHz) frequencies. Similar RF power levels obtain for single transmitters (1 MW at 2.38 GHz) in large area reflectors (Arecibo). Yet we wish to extrapolate to GW level systems. We will try to mentally converge these various factors into a current day estimate of what future power transmission systems may cost.

V. RIGHT-OF-WAY ISSUES

Conventional power transmission line systems could not exist as effectively as they do without the concept of right-of-way. Limited access corridors are needed for public safety as well as convenience and necessity for power delivery. Wireless power transmission systems are no different in some respects, but are different in others.

Wireless power transmission beams need to occupy free-space in order to

efficiently transmit power from one location to another. The taking of space may involve the issue of right-of-way, even though no land is involved except for the terminal sites. To my knowledge there is no current legislative authority for right-of-way agreements for space power beams.

This is a potentially serious problem, due to the uncertain economics attendant to possibly frequent beam interruptions but also from the beam power safety standpoint, since there is no visible indicator of the power transmission beam except at the transmitter and receiver. How can one avoid the beam if you cannot see it? Humans do not perceive microwaves for example or IR beams, except as heating results, and then it may be too late. Even optical wavelength laser beams in space are invisible, except for the occasional debris scatter. How does one post a ROW warning in space of no trespassing or keep out due to danger?

There is no official map for proposed future beamed power sites for example as the beams leave the Earth's surface, transit to GEO reflectors and re-transit space to return to the ground based rectenna site. Such official maps could preclude tether transportation swaths interfering with dedicated beam power space-corridors as an instance of future ROW planning on a World scale.

However, dedicated, shared or controlled access beamways or tether swaths may be possible if properly engineered and maintained. This would be similar to ac power distribution lines and cable-TV sharing the same utility poles.

For space enterprises that in the future may depend upon beamed power such as Earth orbiting facilities and Lunar colonies, the concept of necessity and convenience may lead to easements for dedicated power beam corridors. Should we expect rapid, unplanned peripheral development near wireless power transmission sites and along beam corridors? Much as retailing

establishments around commuter line terminals. After transportation in space the next most desirable commodity is power in space.

The Dutch East India company radio transmitters had their transmitting antenna patterns seriously modified by clever adjacent households tapping into the launching beam pattern for light bulb excitation with careful wire placements. TVA had similar problems with unauthorized open transformer couplings on some of their transmission lines.

Whereas cost of ROW for the OWL and buried cable systems are included in the systems costs, and the terminal sites costs for PRS are included, any WPT ROW cost for the portion of the beam through the atmosphere and in space are not included, as they are undefined at present.

The issue of beam right-of-way needs further consideration in support of wireless power transmission systems economics and safety. The increasing difficulties of obtaining economic ROW for land transmission lines may make PRS systems more attractive in the future.

VI. COST DATA PLOT

The Figure shows a scatter plot of various systems actual and estimated costs. They are not all equally well scrubbed for inflation adjustments, but for the known, long ago legacy estimates, their costs have been inflated based upon a 3.1% annual average. Comparable safety and interference levels have been assumed for the various types of transmission, although this is difficult to equate. In some cases it is also difficult to sort out recurring costs versus non-recurring costs estimates.

As far as is known, the power transmission system maintenance and operating costs are not included, only the

installed capital costs. The costs of tree trimming for OWLs, submarine cable-anchor drag repairs, and seismic displacement realignments for the waveguides come to mind. Also, the beamed power system must contend with the clean up costs for deposited avian guano, among other debris that floats or crawls or grows onto fixed structures with their operating faces pointed skyward such as the transmitters and rectennas.

The economies of scale tend to drive the FOM cost lower for higher power levels with the under sea cables. Once the basic terminal sites and equipment are in place, the higher capacity cables are less of a cost item per unit of power. Similarly for the beamed power systems. This is because once the sunk capital investment in the terminal sites, safety equipment QOS energy storage and the basic DC to RF and RF to DC converters are made, then it behooves the WPT system operators to push through the system as much power as possible. Probably limited only by RF breakdown voltage levels in the beams at stratospheric altitudes, for example: $\sim 5\text{W}/\text{cm}^2$ at 1 GHz at 55km, $\sim 800\text{W}/\text{cm}^2$ at 10 GHz at 38 km altitude, (vs. $1.2\text{MW}/\text{cm}^2$ near the Earth's surface). Most current PRS studies have over 30 dB of power breakdown margin at 4GW output levels.

The well engineered OWL systems FOM costs tend to be independent of power level to first order, and principally reflecting right-of-way costs in addition to the equipment costs.

All of the wired power transmission systems are designed to be equally adept at transmitting power in either direction (not simultaneously). However, with few exceptions [19] the wireless power systems as currently envisioned can only transmit power in one direction. Thus, WPT value is less than wired systems for the same power handling magnitude, in regards to an electric utility's flexibility of changing power flow direction.

VII. CONCLUSIONS

Crude as it is, the scatter plot reveals that there is a thread of relationships visible, breaking into four different categories of under sea cables, underground waveguides, beamed power systems and open wire lines.

We conclude that open wire lines are the lowest cost means of electric power transport for point to point on the Earth's Surface for less than about 10GW levels and overland. OWLs also have the highest system transmission efficiency, or order 95%. Wireless power transmission system efficiencies may not exceed 65% for the overall system, converters and optics included, due to diffraction and conversion losses.

When the path is mostly over water as in the long intercontinental distances, then power relay satellite systems may have an advantage relative to the alternate undersea cable systems, even discounting the currently optimistic cost estimates for beamed power systems.

For the short intercontinental distances such as over straits, the undersea cable is more cost effective at the short ranges and modest power levels, but again wireless power transmission may be cost effective at higher power levels, if beamed power safety concerns can be mitigated.

The TE01 circular waveguide cost estimates are intermediate between undersea and beamed power for Gigawatt level power transmission, but we only have cost estimates for underground installation, not undersea. Thus we cannot really compare TE01 waveguide underwater intercontinental costs, but beamed power via relay satellites appears to be lower cost for high power, long haul circuits in view of the waveguide straightness requirements.

VIII. RECOMMENDATIONS

Huge space mirror structures of several hundred meter to several kilometer diameter and their difficult control systems will be needed for enabling wireless power relay reflectors in orbit. Research and development for these large orbiting mirror structures is needed.

Very reliable beam intrusion detection techniques and equipment are needed to assure beam safety. Also the companion energy storage devices and switches are needed to provide quality of service power delivery to customers whenever the power beam must be interrupted.

Wireless power transmission beams right-of-way policy needs to be developed in the context of safety, public necessity and convenience. Legislative jurisdiction needs to be established. Key corridors such as equatorial sites need to be preserved. Such actions could reduce the economic uncertainty in utilizing WPT in PRS systems and other space and airborne ventures.

A significant shortfall in the current wireless power transmission capabilities is the inability to utilize the terminal equipment to alternatively either transmit or to receive. Currently, phased arrays or rectennas can only do one function or the other, not both.

There is no fundamental reason why the equipment cannot have its electric current flow direction stay the same, while the polarity of the voltage is changed, thus operating in reverse. Admittedly, 50 and 60 Hz power line ac-DC solid state converter equipment operates in this fashion, and it is currently a stretch for microwave devices. However, we recommend that research be applied to this area. Intercontinental time-zone supply-load leveling could thus be accomplished with PRSs.

Life cycle costs of the various systems need to be generated and compared, not just capital costs. It would be interesting to compare maintenance and operating costs of the four basic power transmission systems, in addition to the installed system costs.

Some effort should be expended to investigate the economics of WPT involving high altitude stationary platforms for supporting elevated reflector beam waveguide systems. They may prove interesting.

More Power To Us.

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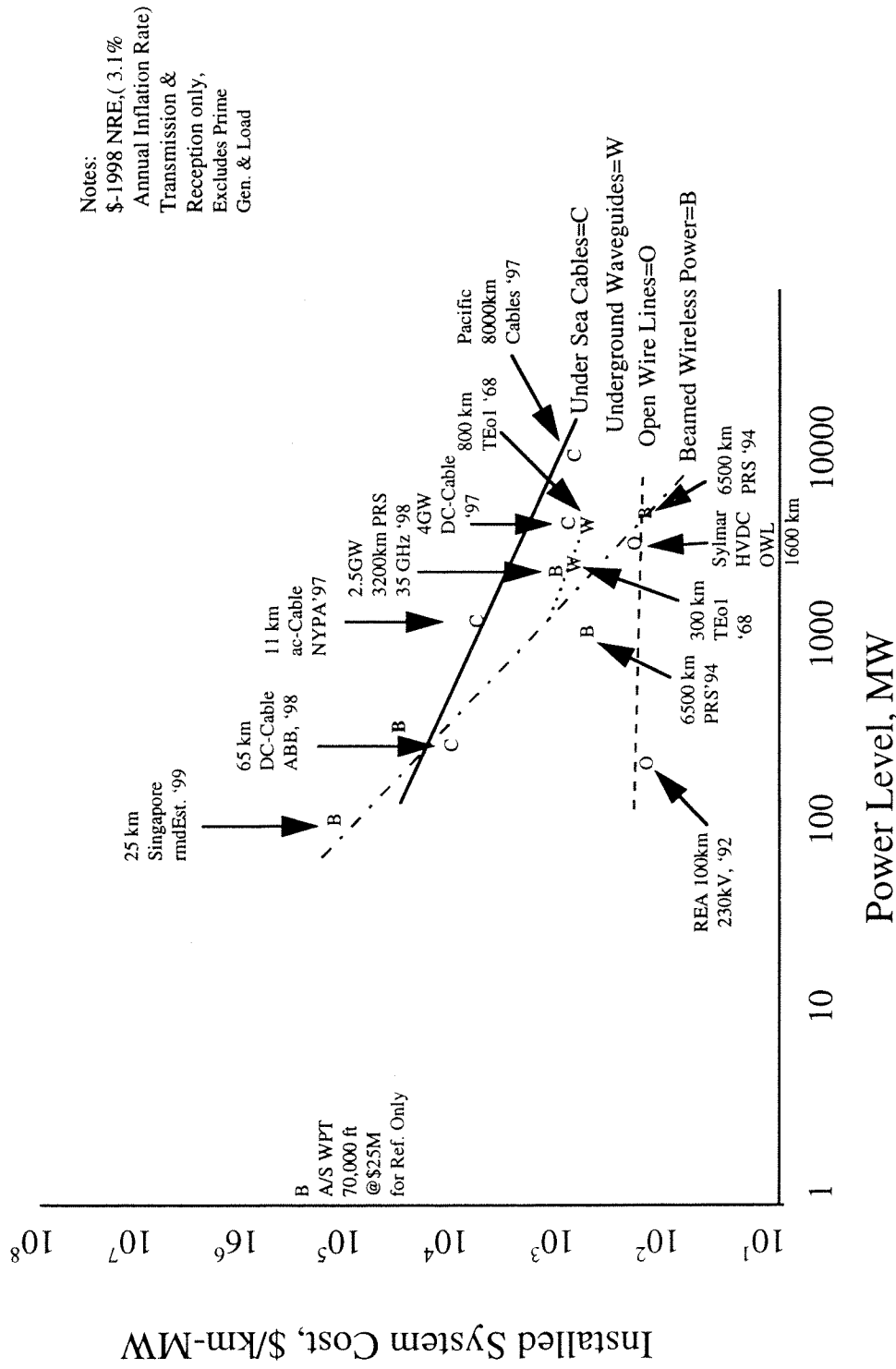
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The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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